BEFORE THE
PUBLIC SERVICE COMMISSION OF WISCONSIN

Application of Highland Wind Farm, LLC, for a Certificate of Public Convenience and Necessity To Construct a 102.5 Megawatt Wind Electric Generation Facility and Associated Electric Facilities, to be Located In the Towns of Forest and Cylon, St. Croix County, Wisconsin	Docket No. 2535-CE-100

Ex.-CW-Cook-8

Please enter the attached exhibit, Ex.-CW-Cook-8, *Analysis of the wind turbine noise emissions and impact on the environment,* by Katinas, Marciukaitis, and Tamasauskiene. Ren. and Sust. Energy Rev. 58 (2016) 825-831. January 2016.

Renewable and Sustainable Energy Reviews 58 (2016) 825–831

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Analysis of the wind turbine noise emissions and impact on the environment

Vladislovas Katinas*, Mantas Marčiukaitis, Marijona Tamašauskienė

Lithuanian Energy Institute, Laboratory of Renewable Energy and Energy Efficiency, Breslaujos Street 3, LT-44403 Kaunas, Lithuania

A R T I C L E I N F O

Article history:
Received 13 May 2014
Received in revised form
15 December 2015
Accepted 17 December 2015
Available online 14 January 2016

Keywords:
Wind turbine
Acoustic noise
Background noise
Noise propagation
Impact on environment

A B S T R A C T

Research of regularity patterns of statistic parameter variation of wind turbine (further referred to as WT) generated noise is presented in the article. The Fast Fourier Transform algorithm for the analysis of the measured data was used to establish the noise spectrum, which was a broadband range. In the noise spectrum, the greatest changes were observed in the frequency range of 200–5000 Hz when WT was operating and when it was not. The level of the wind turbine noise increases as wind velocity increases. But the level of this spectrum decreases under all frequencies when the distance from wind turbines increases.

The literature data analysis reveals that the intensity level of WT generated acoustic noise depends on aerodynamic processes and mechanical noise intensity of its element flow. While estimating WT generated noise level, it is necessary to consider the background noise level evoked by wind, which significantly depends on wind flow velocity. When there are high wind speeds, WT generated noise is concealed by the background noise level evoked by wind. It was determined that WT generated noise level, when wind speed is $v \approx 12$ m/s, and when there distance is greater than 100 m to the WT tower, it becomes equal to the background noise level. In such cases, the influence of WT noise on the environment could be underrated. Experimental and theoretical investigations of the WT generated acoustic noise were carried out. A methodology was developed, and a mathematical noise propagation model, which enables to forecast WT generated acoustic pollution level in residential places or other selected areas, was presented.

Contents

1. Introduction

At present time, wind energy is one of the most rapid developing electricity production fields worldwide. In 2014, total capacity of installed wind WT was 336,327 MW, out of which approximately 128,751 MW was installed in the EU countries [1,2]. In Lithuania, at

* Corresponding author. Tel.: +370 37 401841; fax: +370 37 351271.
E-mail address: res@mail.lei.lt (V. Katinas).

http://dx.doi.org/10.1016/j.rser.2015.12.140

the end of 2014, total capacity of installed WT comprised approximately 279 MW, and WT produced 6% of total electric power consumed in the country.

Wind power is now an undisputed pillar of electricity in many parts of the world. Wind energy installed worldwide can now contribute close to 5% of global electricity demand and significantly reduce CO_2 emissions. Such fact must be evaluated, because in the last few centuries, the concentration of greenhouse gases (GHG) has been rising in the atmosphere. According to [1,3,4], concentration of GHG is increasing due to increase in use of fossil fuels. The surface temperature has globally increased by 0.4–0.5 °C; the sea level has also risen at an average annual rate of 1–2 mm during this period [3,4]. Power sector is contributing 65% of the total CO_2 emission [1]. It is evident that the WT generated energy significantly improves the environmental conditions.

Also, wind energy development is inevitably related to certain negative environmental impact, since when operating, WT generate acoustic noise. World Health Organization recommends when estimating WT environmental impact to evaluate the noise impact at low, average and high-frequencies. Low-frequency sounds and infrasound excite individual human body parts and worsen general human well-being. It is known that the noise of 32 dB(A) for some people is a strong irritant for their nervous system, whereas the noise of 40 dB(A) and higher for most people evokes strong discomfort [5–7].

Research data of WT acoustic noise reveal that their evoked noise may be distributed into two main sources: mechanic and aerodynamic noise [8,9]. Mechanic noise is evoked by moving parts inside the cabin – gearbox, cabin rotation mechanism, etc. Aerodynamic noise originates due to air current changes, occurring due to the flow on the rotor blades [9]. The airflow turbulent pulsations, which are produced by flow behind the blades and changes of the flow in the boundary layer on the surface of the blades etc. produced this noise [6,8,9].

Besides, aerodynamic pulsations are developed due to rotating interaction of blades with construction elements of WT tower. Noise may be broadband and tonal. Besides aerodynamic and mechanical noise, there always exists the environmental background noise, which is conditioned by wind flows of the plants, relief incongruities and other obstacles, transport means, birds, industry objects, etc. [9,10]. The background environment noise intensifies during the day, whereas at night, it sometimes diminishes due to lower side effect impact (evoked by transport, factories, fauna, etc.) [6,10–12]. The measured data show the wide range in sound levels at the residence. The WT produce more sound at higher wind speeds, and it was thought that the higher wind speeds would provide more background sound, which in turn would mask the increasing wind turbine noise level [11].

Performed research of Enercon E 82, Enercon E 70, Nordex N 90 and other WT's [13,14], when wind velocity changes from 4 m/s to 10 m/s, indicates that intensity of WT noise depends on the absorption of atmosphere and earth surface sound pressure pulsations, reflection, topographic earth surface effect, metrological conditions and many other agents and factors. It was determined that high-capacity (1 MW and more) WT generate much higher noise than those of low-capacity (250 kW and less). With the increase in distance from WT, the intensity of noise diminishes [13–15]. Noise is better absorbed by light earth surface than the solid one. Moreover, the surface absorption very much depends on the noise frequency [16]. In noise frequency range from 100 Hz to 1000 Hz, the biggest noise absorption [15,17] is observed. Suppression of noise is performed by reducing the noise level in its origin source, also by building architectural structural means, planting various sprouts. In order to avoid hazardous environmental impact, it is expedient to precisely understand physical origin of its acoustic noise, to investigate dispersion patterns and apply noise reduction means.

Research of WT spread noise suppression processes and regularity patterns of variation of statistical parameters of the environment background noise are provided in the article. The methodology is developed, and mathematical noise propagation model is submitted, which enables to forecast the level of WT acoustic pollution in residential places or other chosen places.

2. Methodology

2.1. Theoretical analysis of the WT noise generation

Intensity of sound is characterized by air mass pressure pulsation wave as energy transmitter. When the sound spreads, these waves transfer energy, which is expressed by average energy flow in any space point. According to the noise spectrum, the noise of low-frequency (up to 300 Hz), average frequency (300–800 Hz) and high-frequency (over 800 Hz) is distinguished. Human hears sounds, the frequency of which is from 16 to 20,000 Hz. The ear best feels 800–4000 Hz sound frequencies. WT acoustic noise is characterized by frequency and intensity level. Sound intensity is estimated in decibels and is calculated using the following formula:

$$L_I = 10 l_g (I/I_0) \tag{1}$$

here I is the measured sound intensity, W/m^2; I_0 is the limitary intensity of sound hearing, ($I_0 = 10^{12}$ W/m^2).

Sound intensity I is expressed as [15]:

$$I = Energy/(time \times area)$$

or

$$I = Power/area \tag{2}$$

Theoretically estimating the intensity of noise in decibels as dispersed by WT, depending on the distance to WT tower, it may be calculated according to formula [18,19]:

$$L_{pj} = L_w - 10 log(2\pi R^2) - \alpha R + L_g, \tag{3}$$

here L_{pj} is WT generated noise level in decibels, dB(A); L_w is the noise intensity spread by WT in axis level; R is the slant distance from rotor center of WT to the actual measurement position; α is the atmosphere absorption coefficient; L_g is the noise level correction due to sound pressure pulsations reflection from the earth surface.

The value of atmosphere absorption coefficient α depends on the environment temperature and acoustic noise frequency. With the increase of the environment temperature or noise frequency, suppression of atmospheric noise increases (for example, at $t = 30$ °C $\alpha = 0.0075$). The speed of sound wave dispersion depends on the properties of the media via which it spreads [9,10,13]. It becomes higher as the density of the media gets higher. For instance, speed wave of hearing frequencies (16 Hz to 20 kHz) in the air is approximately 340 m/s.

Theoretically calculated level of noise, depending on the distance up to WT, at different values of atmospheric absorption coefficients α, reveals that the impact of coefficient α on WT generated noise level is more intensively reflected at a higher distance to the WT tower. The size L_g of noise level correction due to the impact of the earth surface on WT installed on land is considered 1.5 dB(A), whereas in the sea – 3 dB(A) [18,19]. However, it is necessary to take into account the fact that in any traditional environment, a background noise also exists, the impact of which should also be estimated when identifying WT noise. Eq. (1) indicates how the level of noise should be estimated in decibels.

Mathematically, decibels are not considered pressure units, since they do not have dimension. Therefore, in order to identify the impact of several sources, first of all, the values of decibels should be converted into pressure real units (in SI system into Pascal (Pa)), afterwards pressure units should be added, and then converted back to decibels.

Total intensity level generated by WT (L_{pj}) and background (L_{pA}) noise are calculated according to formula [19,20]:

$$L_p = 10 l_g \left[10^{(0.1\ L_{pA})} + 10^{(0.1\ L_{pj})}\right], \quad (4)$$

here L_{pA} *is* the background environment noise level, dB(A); L_{pj} *is* WT generated noise level, dB(A).

WT generated noise level having total noise level is calculated from the following equation:

$$L_{pj} = 10 l_g \left(10^{(0.1 L_p)} - 10^{(0.1 L_{pA})}\right). \quad (5)$$

Literature sources [10,21–25] demonstrate that WT acoustic noise level is rather high. All this should be considered when constructing WT, since noise level should comply with normative requirements, i.e., to not exceed a 45 dB(A) level in the residential areas [26,27]. The level of WT noise at rotor axis height depends on WT type, tower height and wind velocity. Enercon type WT noise level varies within the limits from 89 dB(A) to 104 dB(A) (Table 1). It may be observed that with the increase of WT capacity or wind velocity, the intensity of the spread noise increases as well.

Value of atmospheric absorption coefficient α at temperature $t = 20\ ^\circ$C and frequency 1000 Hz is approximately 0.005 [25,28]. However, this coefficient value α depends on environment temperature and acoustic noise frequency.

Theoretically estimated noise level depending on the distance to WT at different absorption coefficient values indicates that the impact of atmospheric absorption coefficient α to WT evoked noise level more intensively is revealed at a greater distance from the power plant (Fig. 1). Besides, it is necessary to evaluate the fact that in any traditional environment, other noise sources prevail as well, the impact of which should be estimated.

In WT farms, in case of several noise sources with different noise levels, the total value of noise will not be arithmetic to the sum of noise levels. In order to calculate the total noise level, correction ΔL is added to the bigger (out of two added) noise level. Thus, the total noise level out of two noise sources will be equal [10,19]:

$$L = L_1 + \Delta L, \quad (6)$$

here L_1 is higher out of the two added noise levels.

Due to addition of several sources, spread of noise occurs, so first of all, two noise sources are identified, the noise levels of which are the highest, and the total intensity of these noises is identified; then the following greatest noise is added to them, etc. Values of correction ΔL, calculated using Eq. (4), are given in Table 2.

Firstly, the maximum noise dispersed by WT is identified, and then its intensity level variation is calculated depending on the distance to the object. Data given in Table 2 reveal that in case when the difference of noises is higher than 10 dB(A), a bigger noise prevails, since the impact of smaller noise on the total noise level does not exceed 0.41 dB(A) value. Measurements of WT noise, taking into account the hygiene requirements [29], are carried out at 1.5 m height from the earth surface.

2.2. Experimental study and measurement technique of the WT noise propagation

Experimental research study was performed for the analysis of WT generated noise and influence of background noise on this process. Enercon E-40 type WT of JSC “Intuva” of Prozariškiai WT-1 power plant was used for the investigation. The WT was low-capacity (up to 250 kW), which was installed in Kaišiadoriai region further from residential areas; the tower height of WT was 65 m, and it was surrounded by agricultural land. There are no big trees or a bush nearby WT. Research was carried out at different wind speeds. Hand-held analyzer type 2250 Bruel and Kjaer was used

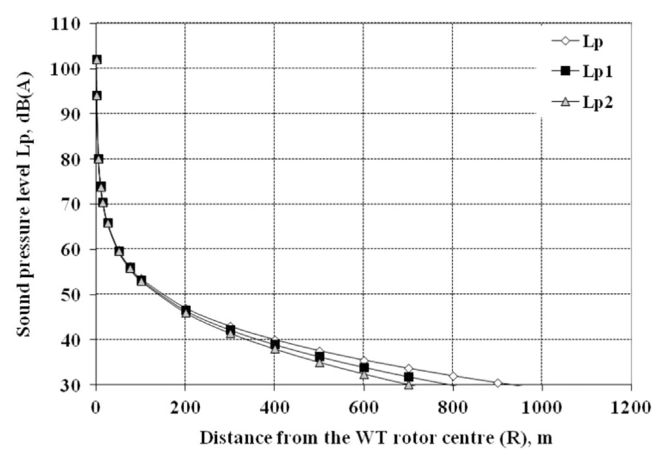

Fig. 1. Theoretically estimated at 1.5 m height above the ground surface noise level dependence on the distance to WT at different atmosphere absorption coefficient values: L_p , when $\alpha = 0.005$; L_{p1}, when $\alpha = 0.0075$; L_{p2}, when $\alpha = 0.01$.

Table 1
The noise level of WT at rotor axis height [21–24].

Wind speed at 10 m height, m/s	Level of noise dB(A)								
	E-82		E-48		N90/2500 HS	N80	SWT-2.3–93	RE power MM82	
	Tower height, m		Tower height, m		Tower height, m	Tower height, m	Tower height, m	Tower height, m	
	78	138	50	76	< 80	< 80		< 80	100
4			89.0	89.9	99.0	98.0		93.0	94.0
5	96.3	98.2	93.3	94.7	102.5	100.5		100.4	100.7
6	100.7	102.6	97.5	98.8	105.5	102.5	105.0	102.3	102.7
7	103.3	103.8	99.2	100.0	106.5	103.0	107.0	103.3	103.6
8	104.0	104.0	100.0	100.0	107.0	103.5	107.0	104.4	104.6
9	104.0	104.0	100.0	100.0	107.0	104.0	107.0	104.9	105.0
10	104.0	104.0	100.0	100.0	107.0	104.0	107.0	105.0	105.0
11					107.0	104.5			
12					107.0	105.2			

Table 2
Values of correction ΔL of two sources' total noise level identification.

The difference of the noise levels. dB(A)	*0*	*1*	*2*	*4*	*6*	*8*	*10*	*15*	*20*
The value of the correction ΔL. dB (A)	3.01	2.54	2.12	1.45	0.97	0.64	0.41	0.14	0.04

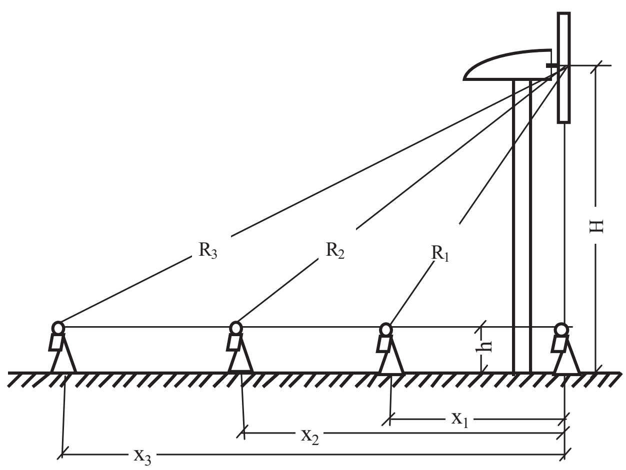

Fig. 2. Measurement scheme of WT acoustic noise towards wind blowing direction.

for the measurement of noise. Frequency analysis software BZ-7223 was used for the analysis of measuring data.

Measurements of acoustic noise were carried out in the wind direction, against the wind direction and perpendicularly to the wind direction at different distances to WT tower (Fig. 2). Distance x from WT tower was changed every 25 m, i.e., it was chosen 0, 25, 50 m, etc. The duration of each measurement at 1.5 m in height from the earth surface continued approx. 5 min. Data were collected in analyzer's memory with the help of BZ 5503 software. Frequency analysis software enabled to use 1/1 octave and 1/3 octave and broadband sound measurements at one time.

Frequency analyzer identified the following spectrum parameters together with full spectral statistics: LX_{eq}, LXF_{max}, LXS_{max}, LXF_{min}, LXS_{min}, here X is the frequency weighting A, B, C or Z. Spectral statistics was reviewed as L_{XYN} percentile spectra, where Y is time weighting F or S (time weighting S is equal 1 s, F – 0.125 s), whereas N is one of the seven defined percentiles. When estimating acoustic noise, the frequencies range of hearing sounds was divided into one octave (1/1) or one third of octave (1/3) broadband. The bands are marked in average geometric frequencies. In this research, the 1/3 octave noise spectrum was used. Its band central frequencies are the following: 12.5; 20; 31.5; 50; 80; 125; 200; 315; 500; 800; 1250; 2000; 3150; 5000; 8000; 12,500; 20,000 Hz.

3. Results and discussions

3.1. The factors affecting WT noise propagation

From the obtained experimental research, it may be observed that the noise level of WT significantly depends on the background noise level. This noise is comprised of anthropogenic and natural factors. When WT was shutdown and wind speed was 12 m/s, the distance from WT tower changing the background noise level L_{Aeq} changed in the limits from 50.3 to 56 dB(A). It may be approximately considered that it was $L_{Aeq} \approx 53$ dB(A). From the data given in Fig. 3, it may be observed that the total noise is rather high. Besides, it should be estimated that the total noise is comprised of two basic constituents, i.e., background noise of environment, which is equal to 53 dB(A) and is evoked by wind whiffs, plus WT generated noise. The total noise was estimated in accordance with Formula (4). Experimental research revealed that in case of insignificant distance from the tower, WT generated noise insignificantly influences the total noise level. The experimental results indicated that a higher wind speed ($v > 10$ m/s) would provide more background sound, which in turn would mask the increasing WT noise level.

The level of WT generated noise at rotor axis when wind speed is 12 m/s and is equal to $L_w \approx 104$ dB(A). When wind speed diminishes, the levels generated by WT and wind background noise reduces as well. WT noise at axis level at wind speed $v = 6$ m/s if compared to wind speed $v = 12$ m/s reduced from 104 dB(A) to 96 dB(A) [10,21–25], whereas wind generated background noise reduced to 36 dB(A). In most EU countries as well as in Lithuania, the allowable maximum noise level is 45 dB(A) [26,27].

Submitted experimental and theoretical calculation data (Fig. 4) reveal that at 6 m/s wind velocity, the background noise level is significantly lower than WT generated noise. Also, WT generated

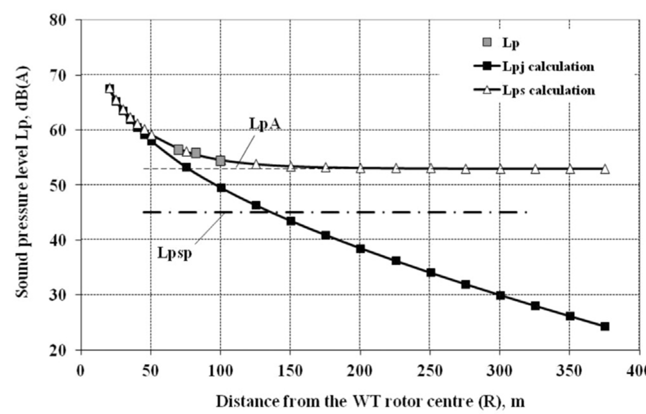

Fig. 3. Change of statistic indicators of acoustic noise at wind speed 12 m/s at WT axis height. L_p are the experimental data; L_{pj} are the data of theoretical calculation according to Eq. (3); L_{ps} is the total noise level calculated according to Eq. (4); L_{psp} is the maximum level permitted according to hygiene norms; L_{pA} is the background noise level.

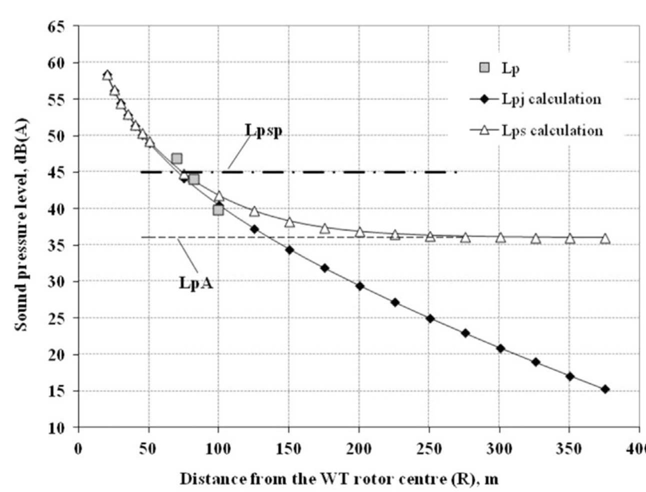

Fig. 4. Change of statistic indicators of acoustic noise at wind speed ~6 m/s at WT axis height. L_p are the experimental data; L_{pj} are the data of theoretical calculation according to Eq. (3); L_{ps} is the total noise level calculated according to Eq. (4); L_{psp} is the maximum level permitted according to hygiene norms; L_{pA} is the background noise level.

noise intensity level is significantly influenced by topographic and meteorological environment conditions [6].

Data given in Figs. 3 and 4 show that the influence of WT generated noise when wind speed $v=6$ m/s to the total noise is reached at 250 m distance to WT rotor axis, whereas at wind speed $v=12$ m/s, this distance reduces to 100 m/s. Thus at wind speed 12 m/s, WT generated acoustic noise insignificantly influences the requirements of hygiene norms.

Research data reveals that in time sequence, the intensity of WT generated noise changes. In some time moments, it may be hardly audible, whereas in other times, rather intensive. It may be observed (Fig. 5) that in certain time periods, noise intensity (LAF_{max}) is higher than the equivalent level (LA_{eq}), at the same time, it may be much lower (LAF_{min}) than the equivalent level (LA_{eq}). The variation of sound level is defined not only in the equivalent level (LA_{eq}) investigated moment.

In Fig. 6, it may be observed how the values of LA_{eq}, LA_{10} and LA_{90} decrease with an increase in distance from the power plant. It is obvious that the mentioned statistic parameters when distancing from WT diminishes, whereas the difference of statistic parameter range changes insignificantly. This shows that acoustic noise was of constant intensity, without clearly vivid maximums.

Formation of WT aerodynamic noise with different frequencies is conditioned by the interaction of blades with airflow near the tower (1–30 Hz pulsations are created), air flow turbulence (creates pulsations 10–400 Hz), blade end edge (create pulsations 500–1000 Hz) [6]. Besides aerodynamic noise, mechanical noise is generated as well. The total noise is also conditioned by background noise, which may be defined as the unit of different frequency and strength sound waves. These waves may evoke unfavorable and hazardous outcomes for human health. Using the Furje transformation algorithm for the measured data analysis, it was determined that total noise is broadband (Fig. 7), which generates at all frequencies. With a greater distance from WT tower, the intensity of acoustic noise reduces.

3.2. WT noise impact on the environment

As it has already been mentioned, in average, human ear hears sounds, the frequency of which is between 16 Hz and 20 kHz. Sounds lower than 16 Hz are called infrasound, whereas higher than 20 kHz – ultrasound [29,30]. Human hearing does not perceive them; however, higher levels of infrasound and ultrasound evoke a feeling of discomfort, and cause harm to human health [5,31]. Human hearing reacts more to a relative change of sound pressure than to the absolute one, thus sound pressure is expressed in logarithm scale by sound pressure level L_p decibels (dB). The level of variation intensity of human hearing sound pressure pulsation is approximately found in the limits from 0 to 140 dB. The sound levels of noise, which are higher than 140 dB, evoke pain and may injure hearing organs [32,33]. Research reveals that WT generated and background noise is a function of wind speed. Processes of aerodynamic noise management are rather complicated. WT mechanical noise processes and their suppression means evoke much less problems than those of aerodynamic.

From the data given in Fig. 6, it may be observed that the biggest sound strength exists in the field of low-frequencies (from 0 to 200 Hz). Further on, when frequencies increases from 200 Hz sound strength intensifies, later it evenly reduces. The noise of different frequencies is generated by flowing the WT rotor blades and other parts, also by the influence of the background noise structure [6].

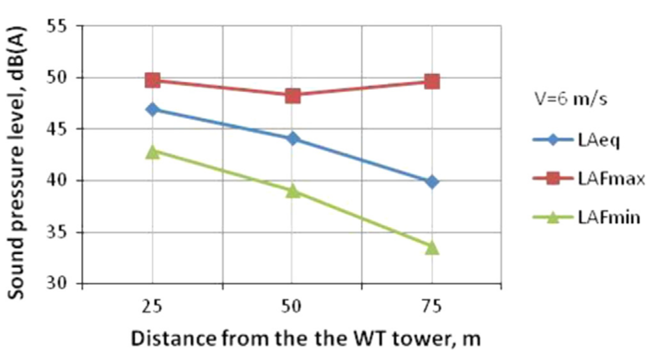

Fig. 5. Change of acoustic noise LA_{eq}, LAF_{max}, LAF_{min} statistic indicators at wind flow speed 6 m/s at different distance (x) to WT tower towards wind blowing direction.

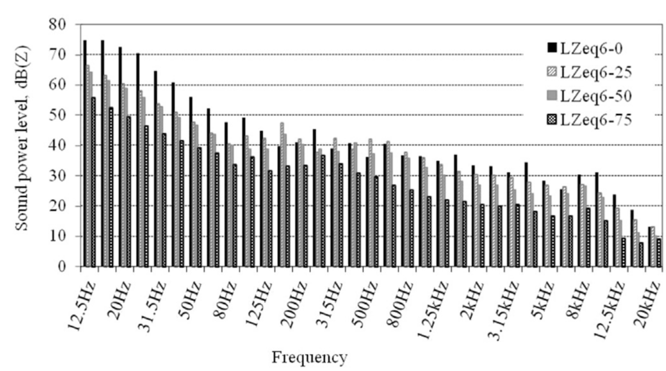

Fig. 7. WT generated acoustic noise spectrum variation at wind speed 6 m/s and distance from its tower: $x=0$ (LZeq6–0), $x=25$ m (LZeq6–25), $x=50$ m (LZeq6–50), $x=75$ m (LZeq6–75).

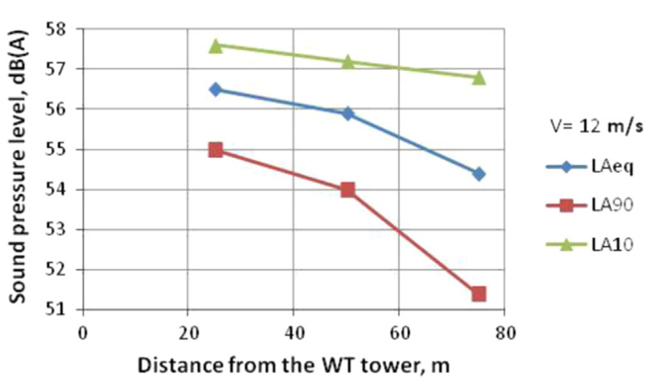

Fig. 6. Variation of acoustic noise LA_{eq}, LA_{90}, LA_{10} statistic indicators at wind flow speed 12 m/s at different distances (x) to WT tower towards wind blowing direction.

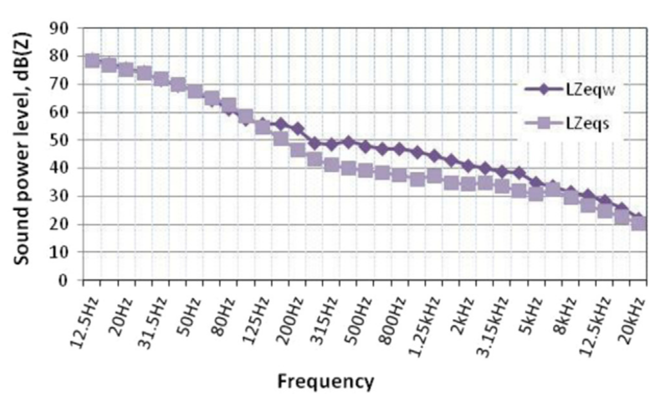

Fig. 8. Variation of acoustic noise spectrum components at wind speed 12 m/s and distance $x=50$ m from WT tower, when WT is not operating (LZeqs) and WT is operating (LZeqw).

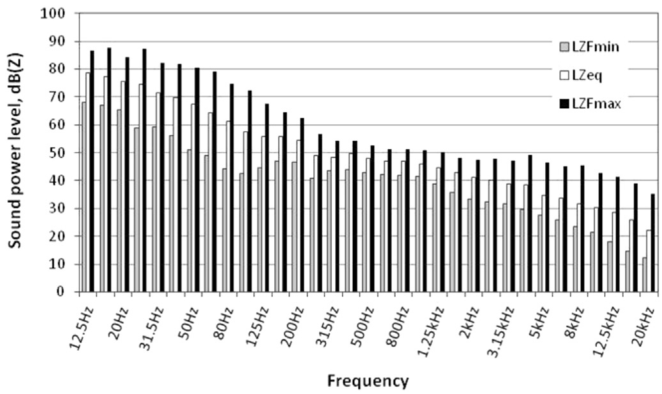

Fig. 9. Variation of acoustic noise spectrum components LZF_{min}, LZ_{eq}, LZF_{max} at wind flow velocity 12 m/s and distance to WT tower $x=50$ m, when WT is operating.

Research indicates (Fig. 8) that at high wind speeds ($\nu \geq 12$ m/s), WT generated noise insignificantly influences total noise level. When WT operates, total noise level at $x=50$ m distance from WT tower is equal to 55.9 dB(A), whereas after stopping WT, it is reduced to 50.3 dB(A). Data given in Fig. 8 shows that WT acoustic noise is generated in frequency range from 200 Hz to 5000 Hz. This is a range of frequencies, where human hearing organs react to noise most sensitively.

We may observe that at stronger wind velocities, WT generated noise is concealed by wind evoked background noise. Energy of sound pressure pulsations when distancing from the source reduces. When a distance from a source doubles in case of space energy dispersion, the level of sound pressure pulsations reduces to 6 dB(A) [8,10]. Research demonstrates that with the increase of noise level by 1 dB(A), the impact is almost insignificant, 3 dB(A) – the impact is perceptible, 6 dB(A) – clearly perceptible impact, 10 – drastically perceptible impact. WT are usually constructed in the open area, thus good conditions for acoustic noise dispersion are developed [19]. When there are relief obstacles or buildings, the expansion of noise is suppressed by these elements.

Data given in Fig. 9 reveals that variation of sound pressure pulsations spectrum constituents occurs due to the same patterns; their level and character vary at all frequencies. Thus, it may be observed that WT generated acoustic noise is comprised of several sound signals. Between maximum and minimum sound, relative value of pressure pulsations remains approximately the same, excluding low (up to 200 Hz) frequency spectrum constituents and very high (over 12,500 Hz) ones.

The character of sound level variation similarly changed when WT was working and when it was not. Thus, it may be observed that the main noise source when wind speed is 12 m/s or higher is the background noise. Besides, the intensity of acoustic noise at a low-frequency zone is much higher than that in the average or high-frequency variation range.

4. Conclusions

Research indicated that when identifying site's total noise, it is expedient to estimate WT generated and background noise levels, the intensities of which are a function of wind speed. Based on the research data, it is estimated that, when wind speed $\nu \approx 12$ m/s and distance to WT tower is bigger than 100 m, WT generated noise level equals to background noise level. In such cases, the influence of WT noise on the environment could be underrated.

The overview and analysis of literature sources reveal that the level of WT generated noise intensity depends on aerodynamic phenomena of construction elements as well as mechanical generation processes of acoustic noise. WT acoustic noise increases due to land surface and acoustic reflection processes of the surrounding constructions, whereas its absorption is influenced by air density, humidity, and by landscape element aerodynamic flow conditions. Using the algorithm of the Fast Fourier transformation for analysis of measured data, it was determined that WT generated noise is broadband; when distance from power plant increases, the sound pressure evenly reduces. Only in the limits of infrasound, low-frequencies and ultrasound frequencies, a small deviation of noise spectrum intensity from the common trend is observed.

It was determined that WT generated sound in the spectrum of pressure pulsations comparing to the greatest changes in the environment noise spectrum occurs in the frequency range 200–5000 Hz. In infrasound, low-frequency (16–200 Hz) and ultrasound frequency ranges, only insignificant changes are observed. Research indicated that at higher wind velocities ($\nu > 10$ m/s), WT generated noise is concealed by background noise level.

Submitted WT generated noise level calculation model corresponds to experimental measurements under natural conditions, thus it may be applied for acoustic pollution level areas or other chosen sites for the assessment.

References

[1] World Wind Energy Association (WWEA). Available ⟨http://www.wwindea.org/hyr2015/⟩; 2015.
[2] EWEA. Wind in power. 2014 European statistics; 2015.
[3] Marimuthu C, Kirubaran V. Carbon payback period for solar and wind energy project installed in India: a critical review. Renew Sustain Energy Rev 2013;23:80–90.
[4] El-Fadel M, Chedid R, Zeinati M, Hmaidan W. Mitigating energy-related GHG emissions through renewable energy. Renew Energy 2003;28:1257–76.
[5] Hanning C. Wind turbine noise, sleep and health. In: Proceedings of paper submitted to the first international symposium on adverse health effects from wind turbines. Picton (Prince Edward County, Ontario): The Waring House Inn and Conference Center; October 29–31, 2010.
[6] Van den Berg GP. Effects of the wind profile at night on wind turbine sound. J Sound Vib 2004;277:955–70.
[7] Taylor J, Eastwick C, Lawrence C, Wilson R. Noise levels and noise perception from small and micro wind turbines. Renew Energy 2013;55:120–7.
[8] Moller H, Pedersen CS. Low-frequency noise from large wind turbines. J Acoust Soc Am 2011;129(6):3727–44.
[9] Rogers T, Omer S. The effect of turbulence on noise emissions from a micro-scale horizontal axis wind turbine. Renew Energy 2012;41:180–4.
[10] Alberts DJ. Addressing Wind Turbine Noise. Lawrence Technological University. Available ⟨http://www.maine.gov/doc/mfs/windpower/pubs/pdf/AddressingWindTurbineNoise.pdf⟩; 2006, 2015.
[11] Van Den Berg F. Criteria for wind farm noise: Lmax and Lden. University of Groningen – Science & Society Group, Nijenborgh 4, 9747AG. Groningen (The Netherlands, Paris); 2008.
[12] Thorne B. The problems with 'Noise Numbers' for wind farm noise assessment. In: Proceedings of paper submitted to the first international symposium on adverse health effects from wind turbines. Picton (Prince Edward County, Ontario): The Waring House Inn and Conference Center; October 29–31, 2010.
[13] Pigeon Top Wind Farm. Supplementary information. Available ⟨http://www.tcirenewables.com/downloads/pigeon_top_supplementary_information.pdf⟩; September 2011, 2015.
[14] Big Thunder Wind Park. DRAFT wind turbine specifications report. Canada, Ontario: Horizon Wind Inc.,; 2011 May 4.
[15] Sacora A. Assessing the noise emitted by small wind turbines. Contemporary problems inropriate technology. Available ⟨http://wind.appstate.edu/sites/wind.appstate.edu/files/Fall2004AdamSacor-a'sNoiseEmittedbySmallWindTurbinesResearchPaper.pdf⟩; 2004, 2015.
[16] ISO 9613-1. Acoustics – attenuation of sound during propagation outdoors – Part 1: calculation of the absorption of sound by the atmosphere. Geneva: International Organization for Standardization; 1993.
[17] Ernest VF Hodgson. Residential wind turbines and noise emission. Contemporaryroblems in appropriate technology. Available ⟨http://wind.appstate.edu/sites/wind.appstate.edu/files/ResidentialWindTurbinesandNoiseEmissions.pdf⟩; 2004, 2015.
[18] Calculation methods in the Danish Statutory Order on wind turbine noise. Available ⟨http://www.es.aau.dk/?id=1132⟩; 2015.
[19] Environmental Noise Booklet. Available ⟨http://www.nonoise.org/library/envnoise/index.htm⟩; 2015.

[20] Noise Measurement Terms. Part 1 – Frequency weighting & level and IEC 61672;2003. Available ⟨http://www.cirrus-environmental.com/noise-measurement-terms/⟩; 2015.

[21] Sound power level E-82. ENERCON energy for the world. Available ⟨http://www.magasbakony.hu/Furged/Fellebbezes_2010-03-30_1.melleklet.pdf⟩; 2009, 2015.

[22] Sound Power Level of the ENERCON E-82 E2. Data Sheet; 2010.

[23] Turbine Sound Power Level Certificates. Available ⟨http://www.eon-uk.com/Kelmarsh_SEI_AppendixD_Post_Submission_Noise_Queries_pt_10.pdf⟩; 2007, 2015.

[24] Sound Power Level of the ENERCON E-48. Operational Mode 500 MW. Data Sheet; 2010.

[25] Acoustics. Attenuation of sound during propagation outdoors. Part 2: general method of calculation. ISO 9613-2; 1996.

[26] Lithuanian norm of hygiene HN 33:2011. Noise limitary in the inhabitable and social destination buildings and near surroundings; 2011.

[27] Miljøministeriet no. 1284, 15. Bekendtgørelse om støj fra vindmøller; December 2011.

[28] Clohessy CM, Sharp G, Vorster F. Evaluation of noise levels of micro-wind turbines using a randomized experiment. In: Proceedings of annual student symposium. Center for renewable and sustainable energy studies. Available ⟨http://www.crses.sun.ac.za/files/services/conferences/annual-student-symposium-2011/2-17nov_clohessy.pdf⟩; 2–17 November 2011, 2015.

[29] Intern. Standard IEC 61400-11. Wind turbine systems. Part 11: acoustic noise measurement techniques; 2012.

[30] Lithuanian norm of hygiene HN 30:2009. Infrasound and low frequency sounds: noise limitary values in the inhabitable and social destination buildings; 2009.

[31] Persson Waye K, Ohrstrom E. Psycho-acoustic characters of relevance for annoyance of wind turbine noise. J Sound Vib 2002;250(1):65–73.

[32] Knopper LD, Ollson CA. Health effects and wind turbines: a review of the literature. Environ Health 2015;10:78. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3179699/.

[33] Pedersena E, Persson Waye K. Perception and annoyance due to wind turbine noise-a dose–response relationship. J Acoust Soc Am 2004;116(6):3460–70.